4.0. GEOLOGY AND HYDROGEOLOGY 2016 ADDENDUM

The WDW-164 and WDW-165 Injection Intervals are being combined for this Petition reissuance into one composite Injection Interval is to address the upward (outside of the casing) movement of wastewater in WDW-164 as noted from recent years' Mechanical Integrity testing. By combining the two previously separate Injection Intervals into one composite WDW-164/WDW-165 Injection Interval, this upward movement now remains within the newly defined composite Injection Interval. To compensate for the inability to adequately quantify the amount of fluid movement entering the overlying (currently defined) WDW-165 Injection Interval, the composite Injection Interval's maximum injection rate will be reduced to 500 gpm to allow the lateral and vertical model demonstrations for the composite Injection Interval to remain valid and conservative. The two previously separate Injection Interval modeling demonstrations have not been combined into a new composite model to allow the current plume and pressure buildup modeling demonstrations (at 500 gpm into each previously separate Injection Interval) to remain very conservative relative to the requested condition of 500 gpm into the composite Injection Interval.

An updated Figure 4-7 is provided which illustrates the proposed composite WDW-164/WDW-165 Injection Interval defined depths. The proposed Injection Zone depths remain the same for the composite Injection Interval (4,715 to 8,250 feet KB) and for the WDW-163 Injection Interval (4,725 to approximately 8,250 ft KB). The composite WDW-164/WDW-165 Injection Interval is now defined as from a base at 8,005 feet KB (open hole log from WDW-164 1-17-81 Schlumberger Dual Induction-SFL Compensated Neutron – Formation Density Log) to a top at 6,600 feet KB (open hole log from WDW-165 3-8-81 Induction-SFL Compensated Neutron – Formation Density Log) and to a top at 6,595 feet KB (open hole log from WDW-164 1-17-81 Schlumberger Dual Induction-SFL Compensated Neutron – Formation Density Log).

Plates 4-1 and 4-2 are dip and strike Geologic Cross Section within 2.0+ miles of the Ineos wells. Plate 4-12 is a local cross-section through the Ineos and an adjacent Class II injection wells. Updated versions of these plates are provided to illustrate the lateral and vertical extent of the proposed composite WDW-164/WDW-165 Injection Interval.

Although the WDW-164 and WDW-165 Injection Intervals are being combined, Plate 4-10 (net sand thickness of the WDW-165 Injection Interval) and Plate 4-11 (net sand thickness of the WDW-164 Injection Interval) have not been revised into a single isopach map but remain split for modeling purposes. Current WDW-164 and WDW-165 Injection Interval lateral plume model thickness values reflect these isopach map thicknesses, and as these models continue to demonstrate conservative plume movements within each interval, the isopach maps have not been changed. Variable thicknesses are used in both the SWIFT pressure and transport models across the areas of the model grids, representative of the mapped thicknesses as presented in each of the geologic isopach maps.

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4.0. GEOLOGY AND HYDROGEOLOGY

The geology and hydrogeology within the extent of the 2-mile radius composite AOR and modeled operational/10,000-year plumes are presented in this section. The discussion includes the regional and local stratigraphic and structural geology, lithology, hydrostratigraphy, and hydrogeology within the Ineos geologic study area. Combined with the results from the Area of Review (AOR) search, plus pressure and flow modeling, the regional and local geologic evaluation demonstrates that injection into the three Frio Injection Intervals by the Ineos wells continues to meet the USEPA geologic and siting requirements for Class I injection wells. This demonstration also identifies the strata within the Injection Zone which will confine fluid movement above the Injection Intervals, and includes a demonstration that this strata is free of known vertically transmissive faults or fractures, and that there is a Confining Zone above the Injection Zone.

4.1. Regional Geology

The Ineos regional geologic study area is located in northwestern Calhoun County on the Texas Gulf Coast. The regional study area is circular with an approximate radius of 20 miles (Figure 4-1). The center of the study area is approximately ½ mile north of the Green Lake, and approximately 14 miles west of Port Lavaca, Texas.

4.1.1 Regional Stratigraphy

Cenozoic sediments that underlie the Coastal Plain of Texas are tens of thousands of feet thick at the coastline (Baker, 1979). These clastic sediments of sand, silt, and clay represent depositional environments ranging from fluvial at the outcrop of most units, to marine in the downdip section where the units may carry a distinctive suite of fossils. Changes in sea level affected the sedimentation source, rate, and depocenter location. These sea level changes are represented in the rock record as facies changes along both strike and dip. Compaction of the marine sediments and subsidence of the depositional basin resulted in thicker accumulation of sediments gulfward in the same stratigraphic unit.

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The stratigraphic units of the Gulf Coast Basin crop out as relatively broad, coast-parallel bands (Figure 4-2) and dip toward the coast between 2-60 feet per mile (Wesselman, 1972). The relative geologic age of these regional surface geologic units becomes progressively younger toward the Gulf Coast. Generally, these bands delineate the coast-parallel depositional framework that has dominated much of the development of the Gulf Coast Basin. In addition, the relative width of these bands reflects the relative thickness of the stratigraphic units, with the broader outcrop bands corresponding to greater thickness. Recent alluvial deposits also occur along the courses of the stream channels.

Surface Geology

The eastern half (Calhoun County) and western third (Refugio County) of the regional study area is covered by ±100 feet of Pleistocene age unconsolidated clay, silt, and sand of the Beaumont Formation. Minor amounts of gravel are also found in the Pleistocene age sediments. Holocene age clay, silt, sand and gravel cover the central portion of the regional study area. The Holocene age sediments were deposited in the floodplain of the Guadalupe River. The Pleistocene Age Lissie Formation is exposed at the surface in the northwestern portion of the regional study. The Lissie Formation consists of sand, silt, clay and a minor amount of gravel. The Lissie ranges up to 200 feet in thickness in the area. The Geologic Atlas of Texas - Beeville-Bay City Sheet - at a scale of 1:250,000 shows change in sediment exposure from youngest sediments of Holocene to the early Pleistocene-age Beaumont Formation (see Figure 4-3). The map from which Figure 4-3 was extracted was prepared by staff of the Texas Bureau of Economic Geology (BEG). No surface faults or folds in strata have been mapped on this atlas sheet within 10 miles of the Ineos facility.

Subsurface Geology

Cyclic depositional units consisting of transgressive and regressive phases, characterize Gulf Coast Tertiary sedimentation. The primary units of concern within the Ineos regional study area are: the Oligocene Upper Vicksburg Group, Frio, Anahuac and Catahoula Tuff Formations; the Miocene Oakville and Lagarto Formations; the Pliocene Goliad Sand Formation; and, the Pleistocene Willis Sand, Bentley, Lissie, and Beaumont

Formations which crop out at the surface. (Refer to the stratigraphic-hydrologic correlation chart provided as Table 4-1.)

Oligocene Units - Upper Vicksburg Group

The Vicksburg Group occurs at a subsurface depth greater than approximately 9,000 feet in the regional study area. Lithologically, the Upper Vicksburg Group in the region consists predominantly of inter-bedded marine shales and sands and is quite variable in thickness, ranging on the order of 200 to 1,000 feet thick. The formation consists primarily of shale, laid down by a transgressive sea in Oligocene time, with some local sand lenses. This thick shale sequence is a relatively impermeable unit, which would prevent any downward movement of wastes. The top of the Vicksburg Group in the subsurface is generally chosen at the first appearance of the foraminifera, *Textularia warreni* (Baker, 1979; and Williamson, 1959). This fauna, however, has an updip limit, which represents the northward transgression limit of the Vicksburg seas. Beyond this limit, the Vicksburg Group becomes non-marine. The Vicksburg Group has not been positively identified in surface outcrop, but may be the non-marine time equivalent of the Oligocene "Frio Clay" and/or the Whitsett Formation of the Oligocene Jackson Group (Baker, 1979 and Table 4-1). In the immediate site area, the only wells penetrating the Vicksburg Group are those which are in excess of a nominal depth of 9,000 feet deep.

Oligocene Series - Frio Formation

The Frio Formation overlies the Vicksburg Group and is one of the major progradational wedges of the Texas Gulf Coastal Plain. The sands of this formation were deposited as old barrier bars, comparable to present day Galveston Island, and/or strandplains or as deltaic facies and fluvial system deposits (Figure 4-4). The Frio Formation extends in a band up to 50 miles wide and in places more than 12,000 feet thick along the Texas Gulf Coast (Galloway and others, 1982). This fact allows injection of waste fluids without excessive pressure increases. The thick sands interfinger with marine shales and with thin discontinuous sands, which were deposited in pro-delta and shelf environments, downdip in the vicinity of the Ineos site. The Frio Formation and lowermost 50 feet (approximately) of the overlying Anahuac Formation comprise the Ineos Injection Zone.

In the Ineos regional study area, the Frio Formation is predominantly a thick unit of calcareous marine sand and lesser shale, and is divided into two to three units based upon the occurrence of indicator fauna. Beyond about 25 miles up-dip and where the transgressive Anahuac Formation cannot be recognized, the Frio Formation inter-tongues or is otherwise indistinguishable from overlying units. It is generally equated in outcrop with the Catahoula Tuff Formation, a pyroclastic and tuffaceous sandstone, but is distinctly separate downdip and in the project area. The Catahoula Formation is referred as the Catahoula Tuff or Sandstone where it outcrops at the surface, but has been divided into the Vicksburg, Frio, Anahuac, and Catahoula units in the subsurface. The Catahoula Formation ranges in thickness from 400 to 600 feet in the subsurface beneath the regional area and consists of clay or tuff with inter-bedded sand. The Frio Formation is 3,000 to 4,000 feet thick in the project area (Figure 4-5). The top of the Frio Formation occurs in the approximate subsurface interval from approximately 4,600 to 6,300 feet beneath the regional study area (Figure 4-6).

The lowermost Frio Formation is less well recognized than either the upper or middle Frio Formation due to the scarcity of fauna, lateral discontinuity of sands, changing sand geometries and scarcity of drilling and log control downdip (offshore). The top of the middle Frio Formation is generally picked at the first occurrence of either *Nonion struma* or *Nodosaria blanpiedi*. The top of the upper Frio Formation occurs below the *Marginulina vaginata* or *Marginulina howeii* fauna, of the Anahuac Formation. This also corresponds with the occurrence of *Cibides hazzardi*.

Oligocene Series - Anahuac Formation

Immediately overlying the Frio Formation is the Anahuac Formation. The Anahuac Formation is a regionally extensive marine transgressive and is one of the most discernible formations in the subsurface. The thick shale sequence of the Anahuac

Formation provides an effective impermeable barrier against any upward movement of waste fluids from the Frio Formation and serves as the Confining Zone for the Ineos Injection Zone. The top of this marine shale formation occurs in the approximate subsurface interval from approximately 4,100 to 5,500 feet beneath the regional study area. The lower 300 feet (approximately) is included as the uppermost portion of the Injection Zone (Figure 4-7). It extends a considerable distance downdip, and for a minimum of 30 to 40 miles updip. The unit is often divided into the *Marginulina*, *Heterostegina* and *Discorbis*, oldest to youngest, based upon the occurrence of these species. The Anahuac Formation is very discernible regionally, being "sandwiched" between the distinctive upper Frio sand below and the Catahoula Tuff Formation above. The Anahuac Formation is minimally 400 feet thick regionally.

Oligocene Series - Catahoula Tuff Sandstone (Formation)

The Catahoula Tuff Formation (Catahoula) immediately overlies the Anahuac Formation. The top of the Catahoula occurs at approximately 3,700 to 5,100 feet beneath the regional study area. The Catahoula is exposed at the surface and has been surface mapped from east at the Sabine River to west at the Rio Grande River. The Catahoula outcrops northwest of the site in Gonzales County, approximately 50 to 60 miles distant (Figure 4-5). At its outcrop, the Catahoula consists of poorly sorted fluvial-deltaic tuffaceous sands, with inter-bedded shales and clays and its thickness, as with the underlying units, increases downdip. Regionally, the Catahoula is approximately 200 to 450 feet thick and probably represents near-shore sands (barrier and beach).

Miocene Series – Oakville Sandstone (Formation)

The Oakville Sandstone Formation (Oakville Sandstone) immediately overlies the Catahoula Tuff Formation. In the regional study area the gross Oakville Sandstone interval varies between 400 and 500 feet in thickness and is about 50 percent sandstone and 50 percent shale (inter-bedded). The top of the Oakville Sandstone occurs from approximately 3,300 to 4,700 feet beneath the regional study area. It has been mapped at the surface as a formation in central Texas (Brazos River to Duval County) and is quite discernible on the geophysical logs, within the project area. The Oakville Sandstone is separated from the Catahoula Tuff Formation by 30 to 200 feet of upper Catahoula Formation shale.

The Oakville Sandstone consists primarily of terrigenous clastics and generally alternating clay (shale) and sand beds. The Oakville Sandstone is a lithostratigraphic unit with well-defined boundaries regionally (Calhoun and adjacent counties).

Miocene Series - Fleming Group

The Fleming Group (Fleming) was deposited as relatively thick continental shale, and immediately overlies the Oakville Sandstone. The top of the Fleming occurs at a depth of approximately 2,100 to 3,100 feet in the regional study area. Many individual sand layers occur within the Fleming Group, which in the study area contain saline water, but because of its relatively large percentage of silt and clay as compared to the Oakville Sandstone, the Fleming acts as a confining unit. The Fleming has also been called the Burkeville Confining System.

In the south-central coastal area of Texas, the Fleming is predominantly marly shale with 10 to 20 percent sandstone in the general form of dispersed beds on the order of 20 to 50 feet thick. The Fleming is distinctive regionally and readily delineated on geophysical logs within study area (Plates 4-1 and 4-2). The Fleming, as with the Oakville Sandstone, is a lithostratigraphic unit and is comprised of terrigenous clastics in updip areas and grades into transitional and marine sediments in the coastal and gulf-ward areas. The Fleming is approximately 1,200 to 1,600 feet thick regionally and is reported to outcrop in DeWitt County, about 40 miles northwest of the Ineos plant (Figure 4-2).

Post Miocene Series

No attempt has been made to delineate the Post Miocene Series of Pliocene, Pleistocene, and Holocene. This is due to the lithologic similarities and lack of paleontological control. However, the Goliad Sand Formation (Goliad) of Pliocene age has been identified in outcrop in southern DeWitt and northern Victoria Counties, 30 to 40 miles northwest of the site (Figure 4-2 and Baker, 1979). Pleistocene sediments generally overlap the Goliad at the surface east of Lavaca County, Texas. Southwest of Lavaca County, the Goliad outcrop width increases due to overlapping of older units in the Rio Grande Embayment (Baker, 1979).

Sediments, predominantly sands, of the Quaternary System, overlie the Goliad. These latter, principally terrigenous, deposits outcrop about 25 to 30 miles northwest of the site near the DeWitt-Victoria County line (Figure 4-2).

Total thickness of the Post-Miocene in the region of the Ineos plant is approximately 2,000 to 2,500 feet. Though the stratigraphic units above (approximately 2,000 feet) cannot be readily distinguished on the cross sections, a hydrogeological distinction and framework of the subsurface spanning these depths can be reasonably well established.

4.1.2 Regional Hydrogeology

The regional hydrogeologic framework consists primarily of three basic aquifers: Jasper, Evangeline, and Chicot (Table 4-1). Two hydrological units, the Chicot and Evangeline aquifers, constitute the principle sources of ground water in Calhoun County. At the Green Lake facility, the Chicot Aquifer occurs from the land surface to an approximate depth of 680 feet (Figure 4-8). Underlying the Chicot Aquifer and extending to an approximate depth of 1,800 feet is the Evangeline Aquifer (Figure 4-9). The Burkeville Confining System underlies the Evangeline Aquifer and extends to a depth of approximately 3,475 feet in WDW-164, which is the top of the Jasper Aquifer. As shown on the regional hydrostratigraphic dip cross section (Figure 4-8), these aquifers roughly represent the Catahoula Tuff-Oakville Sandstone, the Goliad Sand, and the Pleistocene-Holocene formations, respectively, along the Texas Gulf Coast (Baker, 1979). A few sands within the Fleming Group are included in the Jasper Aquifer; however, much of the Fleming is equivalent to the Burkeville Confining System of the Texas Gulf Coast (Baker, 1979), and is not known to yield water to wells in the regional study area

(Wesselman, 1972). Precipitation on the outcrop areas serves as the primary source of recharge to the aquifers. However, due to the low permeability of the Beaumont Clay, areas that are overlain by this unit receive little or no direct recharge from the land surface. Only the Chicot and Evangeline Aquifers produce usable quality water (less than 3,000 milligrams per liter dissolved solids) within the regional study area. Ground water in the Chicot and Evangeline Aquifers in the regional area moves from areas of recharge (northwest) toward the coast (southeast). Water level data collected in water supply wells in the local area support this conclusion. Many of the water wells located northwest of Green Lake are artesian, while water wells southeast of Green Lake have water levels which are 10 to 20 feet below ground surface. Figure 4-9 shows the approximate base of the Evangeline Aquifer.

4.1.3 Confining and Injection Zones

Confining Zone

The Confining Zone for Ineos' injection wells is the uppermost 200 feet (approximate) of the Anahuac shale. The depth to the top of the Confining Zone below the Ineos facility is from approximately 4,520 feet to 4,530 feet below ground level. The Anahuac Formation is a wedge-shaped rock unit that occurs only in the subsurface and thickens towards the coast; is laterally continuous across the regional study area; and consists of shale with occasional thin beds of sandy shale, calcareous shale, and lime.

Injection Zone

The Injection Zone for Ineos' three injection wells comprises the entire sandy section of the Upper, Middle, and Lower Frio Formation (Frio). The Frio consists of inter-bedded sands and shales that are approximately 3,500+ feet thick at the injection well sites. The permitted Injection Zone depths for the Ineos wells are as follows:

WDW-163	4,725 to 8,250 feet BKB
WDW-164	4,715 to 8,250 feet BKB
WDW-165	4,715 to 8,250 feet BKB

Injection Interval

Various portions of the lower section of the Frio Formation comprise the Injection Intervals for each of the Ineos injection wells. The lower sands and shales within the Frio have a gross thickness of approximately 2,000 feet at the injection well sites. The petitioned Injection Interval depths for the Ineos wells are as follows:

WDW-163	5,370 (was 5,422) to 5,710 feet BKB
WDW-164	7,435 to 8,005 feet BKB
WDW-165	6,600 (was 6,750) to 7,500 feet BKB

4.1.4 Regional Structural Geology

Surface elevation across the regional study area is between 0 and 100 feet relative to sea level (Figure 4-12). The topography is low-relief and dissected by southeastward flowing rivers and creeks.

A northwest to southeast regional structural Dip Section (Figure 4-10) and a southwest to northeast regional structural Strike Section (Figure 4-11) are included in this application. On these two published cross sections, strata from the Tertiary to the Pleistocene are illustrated. However, the strata above the Frio Formation have been lumped together as "Upper Oligocene – Pleistocene Series." These cross sections show the regional stratigraphic and structural character of the Ineos Injection Zone.

Figure 4-13 presents the major structural elements of the Gulf of Mexico Basin. The Ineos facility is located on the northwest-southeast trending San Marcos Arch between the Rio Grande Embayment and the Houston Embayment. The depth to the top of the Upper Tertiary System (Pliocene Series) is estimated to be about 15,000 feet in the central basin. This is in contrast to a depth of about 1,000 feet to the top of the Pliocene Series in the study area.

More pertinent to the subsurface geology of the region are Figures 4-10 and 4-11. As shown on the subject Figures, regional dip is to the east-southeast (gulfward) at about 120 feet per mile and major growth faults are essentially parallel to the bed strike and coastline. Faulting is normal and predominantly down-to-the-coast. The major fault zones of interest in this study are the Vicksburg and Frio-Anahuac Flexures. As these faults have generally developed contemporaneously with deposition, faulting has largely controlled the depositional patterns and sand bed geometry of mid-to-lower Frio. In general, sands of the Frio Formation thicken markedly into the downthrown sides of the faults. This applies to both major and lesser complementary or antithetic faults. Regional structural cross-sections showing total thickness of the sedimentary column suggest that most fault displacement, if present under the regional study area, died out during deposition of the Miocene-upper Oligocene facies. Some southwesterly trending faults of the region have probably been active to modern time. Evidence includes interpretations of linear trends visible on the surface (Figure 4-14 - Lineament Map of the Project Area); however, no earthquake data has been recorded for the region (Section 4.1.5).

The Vicksburg Flexure is the most notable down-to-the-coast fault system and extends from the Rio Grande River northward through Victoria County. This flexure is roughly 15 miles north of the Ineos injection wells. Major displacements vary from 4,000 feet at Vicksburg depth to 1,000 feet at the top of the basal Frio. The flexure appears to die out into numerous en echelon smaller faults in Nueces and Victoria Counties.

The Frio Flexure is located nearer the coast and is not as distinct or delineated as the Vicksburg Flexure (Holcomb, 1964; Johnson and Mothy, 1957). Its trace appears to be 10 to 15 miles south of the injection wells. Portions of commercially available maps showing the structural top of the Frio and any mapped faults within the regional area are included as Figure 4-15.

Plates 4-1 and 4-2 are dip and strike Geologic Cross Section within 2.0+ miles of the Ineos wells. Plate 4-3 depicts the location and orientation of the dip and strike Cross Sections. Plates 4-4 and 4-5, respectively, present structural contours on the top of the Confining Zone (Anahuac Formation) and the Injection Zone (approximately 300 feet above the top of the Frio). These drawings serve to confirm the larger regional picture and discussion above. Up-to-the-coast and down-to-the-coast faulting are depicted, and with minor exception, are confined to sub-Anahuac and sub-upper Frio Formation depths. The nearest faulting postulated to cut the Anahuac Formation is located more than five miles to the northwest from the Ineos wells. General thickening on downthrown fault blocks is also evident. Due to lack of well/log control, major versus antithetic faulting cannot always be determined at depth and these relationships may occasionally be obscured. Faulting at depth is quite complex at depth in the area of the Green Lake, Sheriff and East Long Mott areas.

There is evidence that fault trends through the region do not allow significant vertical migration of fluids above the Catahoula Tuff Formation (Catahoula); the Catahoula is approximately 1,500 feet below the deepest underground source of drinking water (USDW) across the region. Evidence for vertical closure includes the presence of trapped natural gas and oil in the Catahoula. The Catahoula and Frio Formations are productive hydrocarbon reservoirs where salt domes and other structural traps exist in the three-county area. Hydrocarbons are not detected in USDWs. If fault trends were active conduits for vertical fluid migration to aquifers and sources of drinking water, buoyant hydrocarbons would be detected in USDW aquifers. Thus, there is no evidence for fluid communication by any natural path between the Frio Formation and USDWs.

4.1.5 Regional Seismic Activity

The central Texas Gulf Coast is an area of minimal seismicity, based on observational data reported from the National Earthquake Information Center (NEIC) of the United States Geological Survey (USGS, 2008). There have been no recorded seismic events within a 30-km (18.6-mile) radius of the subject injection wells, as indicated by the NEIC earthquake search results included as Table 4-3.

In addition, according to a map devised by S. T. Algermissen (1969), the Ineos facility is located within an earthquake risk area zone of zero (0), which represents an area where no damage is expected as a result of earthquake activity (Figure 4-16). This is because movement along active fault planes in the Texas coastal zone is very gradual, hence, earthquakes are not considered to be a significant hazard for this area (Brown and others, 1974). This is in sharp contrast to the sudden and abrupt movement along highly active California type fault zones which produces earthquakes of greater magnitude which can result in extensive damage to areas even a great distance from the fault.

Based on: (1) a history of no recorded seismic activity (intensity and magnitude) within the area; (2) information regarding geologic structures (faulting) within the subject area; and (3) the lack of reports regarding damage associated with seismic activity in the area, seismic activity within the regional study area should have no impact on injection well activity at the Ineos facility. In addition, given the Injection Interval permeability and lateral continuity, injection at the Ineos facility should not generate any noticeable seismic events. This is supported by a 26+ year injection well history at the Ineos WDW-163, WDW-164 and WDW-165 injection wells, with no record of any recordable seismic events within an 30-km radius of these wells.

4.1.6 Regional Ground Water Flow

Ground water in the Coastal Plain aquifers is considered to have two origins: meteoric waters - precipitation that enters the shallow aquifers by infiltration, and formation waters - water trapped in sediments from the original depositional environments (Kreitler, 1979). These two types of waters co-exist in the basin in the following three hydrologic regimes: 1) the uppermost permeable strata are continuously recharged by meteoric waters forming a fresh water regime, which may extend to a depth of several thousand feet below land surface, and where flow is directed downdip toward the basin center; 2) the underlying compacting strata expel original formation water or water at least several million years old from sediments forming a hydrostatic system, where waters from this essentially saline section can come in contact with the overlying meteoric sections to prevent excessive pressure buildup within the hydrostatic zone; and 3) further downdip, the underlying strata represent the over-pressured or geopressured zone where abnormally high fluid pressures exist due to restricted drainage conditions (Kreitler and Richter, 1986).

Kreitler and Akhter (1987) conducted a geohydrologic characterization study of the Frio Formation to evaluate pressure regimes and their influence on the migration potential of formation fluids. The study utilized pressure data gathered from drill stem tests and bottom-hole pressure measurements in onshore oil and gas wells along the Texas Gulf Coast. The data were used to construct potentiometric surfaces and residual potential surfaces and to assess the effects of depressurization caused by hydrocarbon production. Figure 4-17 is a regional hydrologic head map, produced from this study, for the 4,000-6,000-foot zone of the Frio Formation from 1975 to 1985. The regional hydrologic head map suggests that the Frio Formation fluid movement is southeast toward the Gulf of Mexico.

4.2. Local Geology

This section addresses the local stratigraphic and structural geology, lithology, hydrostratigraphy, and hydrology pertinent to the current Ineos injection operations. For the purposes of this demonstration, the local geologic area of study is defined as the area within the 2.0-mile radius composite AOR and 10,000-year plumes. Plate 4-3 shows the local study area, artificial penetrations within the area, and the locations of the local cross section lines constructed for this demonstration.

4.2.1 Local Stratigraphy

The eastern and northern plant site is situated in the Gulf Coastal Plain on an outcrop of the Pleistocene Beaumont Clay Formation (Figure 4-3). The Beaumont Clay Formation (Beaumont) represents a period of active fluvial transportation and deposition of material mainly along stream channels, point bars, natural levees, and backswamps, and to a lesser extent coastal marshes and mud flats (Aronow and Barnes, 1982). The Beaumont is predominantly clay and silt, with some sand (Wesselman, 1972). The Beaumont extends to a depth of about 300 feet and conformably overlies the Pleistocene Montgomery, Bentley, and Willis Formations (see Table 4-1). The western portion of the local study area is located within the floodplain of the Guadalupe River and is covered by Hollocene alluvium (clay, silt, sand and gravel).

All of the beds below the ground surface and above the Fleming Group are composed of sand, silt, clay, gravel, and shale. For the purpose of this report these horizons remain undifferentiated in the subsurface. The undifferentiated Post-Miocene Formations include: the Goliad Sand (Pliocene) and the Willis Sand, Bentley, Montgomery and Beaumont Clay (Pleistocene).

Descending, the Fleming Group of the Miocene Series is found to extend to a depth of 2,200± feet below the Ineos facility. The Fleming Group is approximately 1,500 feet thick in the local study area. The Fleming Group was deposited as relatively thick continental shale, and immediately overlies the Oakville Formation.

The Oakville Formation occurs at a depth of 3,700± feet below the Ineos facility and is approximately 400 feet thick in the local study area. The Oakville Formation consists primarily of terrigenous clastics and generally alternating clay and sand beds.

Below the Oakville Formation is the Catahoula Tuff Formation. The Catahoula is encountered at a depth of 4,100± feet below the Ineos facility and is approximately 450 feet thick in the local study area. The Catahoula consists of poorly-sorted fluvial-deltaic tuffaceous sands, with inter-bedded shales and clays.

The Anahuac shale, a 500-foot thick impervious bed of considerable area extent, is found below the Oakville Formation and rests directly on the Oligocene Frio Formation. The Anahuac shale occurs at a depth of 5,050± feet below the Ineos facility. The upper part of the Anahuac shale is the Confining Zone for the Ineos injection wells. Plates 4-4 and 4-6 show the structural top and gross formation thickness, respectively, of the Anahuac shale Confining Zone.

Below the Anahuac shale is the Frio Formation (Frio). The Frio consists of massive sands inter-bedded with thick beds of shale with a minor degree of inter-bedded sand, shale and sandy shale present in the upper and lower zones. Separating the upper and lower zones, the middle part of the formation contains a greater degree of shale inter-bedded with comparatively thin beds of sand and sandy shale. The Frio Formation is encountered at a depth of 5,120± feet below the Ineos facility and has a gross thickness of about 3,500 feet. The entire Frio Formation has been designated as the Injection Zone. Plate 4-5 shows the structural top of the Injection Zone. Plate 4-7 shows the structural top of the Frio Formation.

WDW-163, WDW-164 and WDW-165 are completed in the Frio Formation. Certain portions of the Frio have been designated as the Injection Intervals for each injection well. Plate 4-7 shows the structural top of the Frio Formation, which mirrors the structural top of the WDW-163 current Injection Interval which is some 300 feet deeper. The top of that shallowest Injection Interval (WDW-163) occurs at a depth of 5,370 feet KB beneath the Ineos site. The top of the WDW-163 Injection Interval occurs about 250 feet below the top of the Frio Formation. Plate 4-8 shows the net sand thickness of the WDW-163 Injection Interval.

Plate 4-9 shows the structural top of the Middle Frio Formation, which mirrors the structural top of the updated WDW-165 Injection Interval, which is some 100 feet shallower. The top of the WDW-165 Injection Interval occurs at a depth of 6,600 feet KB beneath the Ineos site. The top of the WDW-165 Injection Interval occurs about 100 feet above the top of the Middle Frio Formation. Plate 4-10 shows the net sand thickness of the WDW-165 Injection Interval.

The top of the unchanged WDW-164 Injection Interval occurs at a depth of 7,435 feet KB beneath the Ineos site. The top of the WDW-164 Injection Interval occurs about 700 feet below the top of the middle Frio Formation. Plate 4-11 shows the net sand thickness of the WDW-164 Injection Interval. The depth to the bottom of the deepest Injection Interval (WDW-164) occurs at a depth of 8,005 feet KB. Below the Frio Formation is the Vicksburg Formation. The Vicksburg consists predominantly of inter-bedded marine shales and sands. As a whole, the unit consists of shale laid down in a transgressive sea in Oligocene time.

4.2.2 Local Hydrogeology

Two hydrological units, the Chicot and Evangeline Aquifers, constitute the principal sources of ground water in Calhoun County. At the Ineos facility, the Chicot Aquifer occurs from the land surface to an approximate depth of 680 feet. Underlying the Chicot Aquifer and extending to an approximate depth of 1,800 feet is the Evangeline Aquifer (Figure 4-9). The Burkeville Confining System underlies the Evangeline Aquifer and extends to a depth of approximately 3,475 feet in WDW-164, which is the top of the Jasper Aquifer.

Usable quality ground water (<10,000 milligrams per liter (mg/L) total dissolved solids) occurs in the area to a depth of approximately 1,550 feet (from electric logs and TCEQ records). None of the water wells in the local study area, however, are completed deeper than 900± feet. The fresh water is primarily from the Chicot Aquifer (Table 4-1), and some wells are artesian.

Sands and shales of the Chicot and Evangeline Aquifers are found everywhere along the Texas Gulf Coast. Individual sands within both units are laterally discontinuous and vary from a few feet to over 100 feet thick. Variability of the sands is attributed to deposition in fluvial, deltaic, and coastal inter-deltaic environments similar to those seen along the modern Gulf Coast. Although sands are each deposited as discrete bodies, marine transgressions and regressions have shifted and stacked the various environments of deposition along strike and dip, causing the sands to overlap and cut into one another. Overlapping and interconnected sands in the Chicot and Evangeline Aquifers allow communication of ground water between them and the formation of reservoirs with vertical and lateral dimensions far exceeding those of each individual sand body.

4.2.3 Lowermost USDW

For the purposes of this Petition re-issuance, a USDW was defined as an aquifer in the Ineos study area which: 1) contains sufficient quantities of ground water to supply a public water system; and, 2) contains fewer that 10,000 mg/L of total dissolved solids (TDS). It is difficult to map the base of the USDW because: 1) surface casings for oil and gas wells are typically set to a sufficient depth to protect ground water supplies containing ground water having less than 10,000 mg/L TDS; 2) all local ground water supply wells are completed into much shallower and much fresher horizons; and, 3) it is typical that wells drilled in the Texas Gulf Coast are not logged across shallow horizons (within the Ineos AOR, most oil/gas wells are logged from total depth to about 1,200 feet to 1,500 feet KB). However, it was possible to develop a cross section map which portrays the base of the USDW using electric logs from wells which were logged above the zone where water salinity approached 10,000 mg/L.

The base of water having less than 10,000 mg/L TDS is usually picked on electric logs as the depth where the deep resistivity log curve in a clean sand first kicks below 4 ohms. Hydrologists contacted at both the TCEQ in Austin and United States Geological Survey (USGS) use a range of 3 to 6 ohms as read from the deep curve on the electric log for the 10,000 mg/L TDS point. Art Hopkins, a log analyst at the surface casing division of the TCEQ, has indicated (verbal communication, 1995) he uses 4 ohms of resistivity for the 10,000 mg/L TDS level, and 10 ohms for the 3,000 mg/L TDS level. Bob Gabrysch (1980), a hydrologist with the USGS office in Houston, uses a 10 ohm kick for the 3,000 mg/L TDS level. Electric log resistivity methods have also been employed by Baker (1979), Ryder (1988), and Turcan (1966) to determine correlations of TDS levels in aquifer systems in the Gulf Coast region.

The shallowest occurrence of a deep resistivity reading of 4 ohmmeters occurs at a depth of 1,575 feet BKB in WDW-163, while the deepest occurrence occurs at a depth of 1,580 feet BKB in WDW-164 and WDW-165. Therefore, the approximate base of the USDW at the Ineos facility is defined as occurring at a depth of approximately 1,580 feet BKB.

Basis for Base of USDW

The Ineos WDW-163, WDW-164 and WDW-165 well logs, and several other well logs shown on the Northwest-Southeast Geologic Cross Section and Northeast-Southwest Geologic Strike Cross Section (Plates 4-1 and 4-2) provide an objective basis for the base of USDW. Selection is made on these criteria:

- Base USDW determined from deep formation electric log resistivity of 4 ohms, which is found at a depth of 1,580 feet BKB in the WDW-164 and WDW-165 injection wells.

- Base USDW is at least as deep as sample descriptions of the base of the Goliad Sand (Pliocene strata).

- Base USDW is defined as the first sediment above the Fleming Group (Largarto) and low resistivity (4 ohm formation water resistivity) that is correlatable between wells in the AOR. In the Ineos WDW-163, WDW-164 and WDW-165 injection wells, the event is at 1,575 feet BKB, 1,580 feet BKB and 1,580 feet BKB, respectively, and defining log character includes a shaly unit which is relatively radioactive (refer to Plates 4-1 and 4-2). Other available geophysical logs within the AOR were reviewed to confirm the depth of the base of the USDW determined for the proposed well. The base of the USDW varies between about 1,500 feet 2.5 miles northwest of the injection wells to about 1,700 feet 2.5 miles southeast of the injection wells.

The potentiometric surface of potable water is shown in Figure 4-18, (Approximate Potentiometric Surfaces Chicot and Evangeline Aquifers) which is a potentiometric map of the Chicot and Evangeline Aquifers in the AOR. The Evangeline Aquifer water surface elevation declines from northeast to southwest across the AOR, from approximately +50 feet on the northeast side to +10 feet on the southwest side, a potential drop of 40 feet in five miles, or 8 feet/mile. The Chicot Aquifer water surface elevation declines from north-central to south across the AOR, from approximately +20 feet in the north-central AOR to 0 feet on the south side of the AOR, a potential drop of 20 feet in five miles, or 4 feet/mile.

4.2.4 Confining and Injection Zones

From the Ineos injection wells, the approximate depths to the various zones of interest for this Petition re-issuance include the following:

*Depth to:	WDW-163	WDW-164	WDW-165
Base of USDW	1,575′	1,580′	1,580′
Top of Confining Zone	4,540′	4,540′	4,550′
Top of Injection Zone	4,725′	4,715′	4,715′
Top of Proposed Injection Interval	5,370′	7,435′	6,600′
Top of Current Injection Interval	5,422′	7,435′	6,750′
Base of Injection Interval	5,710′	8,005′	7,500′
Base of Injection Zone	8,250′	8,250′	8,250′

* Note: depths are relative to Kelly Bushing (KB)

Confining Zone

The Confining Zone for Ineos injection wells is the Anahuac Formation, with the exception of the lower 300 feet (approximately), which is included as the upper portion of the Injection Zone (Plates 4-1 and 4-2). A structure map of the top of the Confining Zone is included as Plate 4-4. A gross thickness isopach map of the Confining Zone is included as Plate 4-6. The top of the Confining Zone shale stratum is located between 4,210 feet and 5,400 feet (KB) (Plate 4-4) within the AOR. The Anahuac shale is approximately 570 feet thick within the AOR (Plate 4-6). This stratum is continuous and traceable within the AOR (Plates 4-1 and 4-2).

The Confining Zone provides an additional layer of confinement strata between the Injection Zone and the base of the USDW. The stratigraphic sequence in the Confining Zone provides an adequate barrier to the upward migration of waste fluids. The Confining Zone is laterally continuous and free of transecting faults or fractures over an area sufficient to prevent movement of constituents into USDWs and contains a formation with sufficient thickness and with lithologic and stress characteristics capable of preventing vertical propagation of fractures. In addition, the Confining Zone is separated from the base of the lowermost USDW by at least one sequence of permeable (Catahoula) and less permeable strata (Fleming) that will provide an added layer of protection for the USDWs.

A full-hole core and three sidewall core samples were obtained in the Anahuac shale during the drilling of WDW-163 (see Appendix E). Because the samples were gray, limey shale, no porosity or permeability tests were conducted. However, it is reasonably safe to assert that effective porosities are probably 1 percent or less, and air or liquid permeabilities are expected to be on the order of 0.1 mD or less. These values are consistent with the less indurated clays found in Recent to Pleistocene deposits which have comparable depositional environments, i.e. pro-delta to marine clays. As such, the probability of any upward vertical migration occurring via primary permeability means is negligible. As discussed above, the Anahuac Formation is a nominal 500 feet thick in the AOR.

The Confining Zone is composed of a formation with sufficient thickness and with lithologic and stress characteristics capable of preventing vertical propagation of fractures. The Anahuac Formation is predominantly shale and is unlithified. As such, the shale is soft and plastic and will "flow" rather than fracture. These lithologic and stress characteristics provide the Anahuac Formation with the ability to prevent the initiation and/or propagation of fractures.

The Confining Zone is separated from the base of the lowermost USDW by at least one sequence of permeable (Catahoula) and less permeable strata (Fleming) that will provide an added layer of protection for the USDW in the event of fluid movement in an unidentified borehole or transmissive fault.

Injection Zone

The Injection Zone for Ineos injection wells includes the entire upper, middle, and lower Frio Formation. The Injection Zone depths for the three wells are from:

WDW-163	4,725 to 8,250 feet BKB
WDW-164	4,715 to 8,250 feet BKB
WDW-165	4,715 to 8,250 feet BKB

A structure map of the top of the Injection Zone is included as Plate 4-5. Plate 4-7 is a structure map on top of the Frio Formation. Plate 4-9 is a structure map on the top of the middle Frio Formation. The Frio Formation is more porous and permeable than the shales of the overlying Anahuac and the underlying Vicksburg-Jackson Formations.

Injection Intervals

WDW-163 Injection Interval

WDW-163 is a perforated completion in the upper Frio Formation. The currently permitted Injection Interval is at the subsurface depths of 5,370 feet to 5,710 feet KB. The revised Petition top of the WDW-163 Injection Interval is also 5,370 feet. WDW-163 is perforated in two sand units (Sand Nos. 3 and 4) between the depths of 5,424 feet and 5,700 feet (Plates 4-1, 4-2, and Figure 4-7). At the Ineos site the upper Frio is comprised of four distinct sand bodies ranging in thickness from 180 feet to about 100 feet in gross thickness. The top of the uppermost sand body (top of the Frio Formation) occurs at a depth of 5,140 feet and is overlain by the Anahuac Formation shale. This uppermost sand is herein termed Upper Frio Sand No. 1 and the successively lower sands are termed Sands No. 2, No. 3, and No. 4. The WDW-163 effective Injection Interval consists of Sand No. 3 and Sand No. 4. Intervening shales are additional barrier strata above this interval. At the site, approximately 180 feet of shale (5,715 to 5,895 feet) immediately underlies Sand No. 4. Ten to twenty feet of shale separate each of the four sands from adjacent sands. These intervening shale beds are generally traceable within the AOR. However, the shale separating Sand No. 4, from Sand No. 3 pinches out downdip to the southeast near the AOR limits (Plate 4-1). Updip, 7,000 to 10,000 feet to the northwest, Sand No. 4 pinches out and is replaced by a shale facies (Plate 4-1). Also updip, some 20,000 feet to the northwest, Sand No. 3 pinches out and is replaced by shale. Downdip (southeast), Sands No. 4 and No. 3 effectively coalesce, culminating in a massive unit of 500 to 600 feet net thickness at the southeastern edge of the local AOR

(Plate 4-8). Plate 4-8 (Net Sand Thickness Isopach Map of the WDW-163 Injection Interval) shows the sand thickness ranging between 20 feet and 600 feet within the AOR.

The shale beds, which comprise the additional barrier strata separating Sands 1, 2 and 3, are traceable within the AOR (Plates 4-1 and 4-2). The 200-foot thick shale lying immediately beneath the Injection Interval (Sand No. 4) at WDW-163 diminishes in thickness until its presence is barely discernible near the southeastern edge of the AOR, and the interval has been mostly replaced by a massive sand unit.

This latter massive sand, which has developed downdip in a stratigraphically lower position than Sand No. 4, has a shale break at its base that separates it from the top of a very persistent, traceable regressive sand unit, termed the Upper Frio Sand No. 6 (Plates 4-1 and 4-2). This sand, in turn, is separated from an underlying regressive Upper Frio Sand No. 7, by 20 to 30 feet of shale. This latter unit appears to lie upon an unconformity updip, or at least a surface of non-deposition, as there is a discernible 150 to 200 feet of extra section below this sand in the downdip sections. General thickening occurs downdip, but it is also found throughout the overall section reflecting contemporaneous sedimentation and subsidence. Thickening is noted to occur on the downthrown side of growth faults in the lower Frio section (Galloway and others, 1982). The net sand map for the WDW-163 Injection Interval (Plate 4-8) does not reflect thickening into any faults due to the apparent inactivity of local faulting during the deposition of the upper Frio section. Lower Frio faults are not evident in the local AOR upper Frio map. Characteristic, progressive thickening does occur downdip, as well as in down-thrown fault blocks, as shown by regional cross sections (Figure 4-8).

WDW-164 and WDW-165 Injection Intervals

The WDW-164 and WDW-165 wells are both screen and gravel pack completions. WDW-164, the deeper of the two wells, is completed in middle-to-lower Frio sands between the depths of 7,485 feet and 7,968 feet with a plug back total depth (PBTD) of

7,980 feet. WDW-165 is completed in middle Frio sands between the depths of 6,802 feet and 7,489 feet with a PBTD of 7,560 feet (Figures 4-7 and 5-3).

The top of the Injection Interval in WDW-164 is at 7,435 feet KB, with the long string casing set to 7,478 feet KB and the screened interval top at 7,485 feet KB. The base of the Injection Interval in WDW-165 is to 7,500 feet KB, with the screened interval base at 7,489 feet KB (see Figures 5-2 and 5-3). A current Petition condition is that no significant flow occurs below a depth of 7,435 feet KB in WDW-165, which is the top of the WDW-164 Injection Interval. The most recent (2008) MIT (Appendix J) and PFOT (Appendix G) indicated that the top of fill in WDW-165 is at a depth of 7,189 feet, with the radioactive tracer (RAT) results indicating flow down to 7,116 feet KB. This is over 300 feet higher than the deepest allowed flow depth in WDW-165. The WDW-164 2008 RAT results indicated that flow is going into the formation no higher than 7,480 feet KB, with the top of fill at 7,489 feet KB. This is 35 feet deeper than the top of the permitted Injection Interval in WDW-164.

Injection testing does not indicate that communication or interference exists between the two wells. The 2008 PFOTs for these two wells do not indicate on their derivative plots any indication of spherical flow exhibited by a negative half-slope, which might indicate vertical flow from an overlying or underlying sand. There is a persistent traceable shale interval present in the overlap interval which appears sufficient for isolation of the two intervals. The traceable shale stratum located in the overlap interval that provides isolation between the WDW-164 and WDW-165 Injection Intervals is present over the interval from 7,410 to 7,430 feet KB in both wells, as seen on their open hole logs (Appendix D). This traceable shale interval is highlighted in green in Figure 4-7 to more clearly identify it.

As shown on the geologic cross-sections, the current Injection Intervals are laterally continuous and traceable. Though traceable, the lower portion of the middle-to-lower Frio current Injection Interval (WDW-164) becomes quite shaly downdip (east and southeast) near the edge of the local AOR (Map ID Nos. 50 and 51). In contrast, to the north and northwest, especially at Map ID No. 17 (Plate 4-1), the lower Frio section becomes very sandy and thickens along with the entire middle Frio and deeper sections. This marked thickening may be related to deep-seated faulting, as may the thickening in the southeast part of the AOR. A net sand thickness map for the WDW-165 Injection Interval is presented as Plate 4-10.

A structure map on top of the middle Frio Formation (just below the revised WDW-165 Injection Interval) is presented as Plate 4-9. At the Ineos site, the updated Injection Intervals for WDW-165 and WDW-164 span the depth interval between 6,600 feet and 8,005 feet. The immediately overlying shale, which comprises the uppermost portion of this effective Injection Interval is readily traceable and, as shown on the strike cross section through the site (Plate 4-2), is generally 25 to 50 feet thick within the local AOR along strike, i.e. northeast to southwest. Similarly, though generally slightly thinner, ranging between 15 to 50 feet in thickness, this shale is also traceable along strike in the extreme southeast area of review. As shown on the northwest to southeast dip cross section (Plate 4-1), however, this shale interval, as well as the sand(s) immediately overlying it, thin markedly to the north and at Map ID No. 41 this shale is 10 feet thick. It appears, in reviewing the logs of wells north of the -6,400 feet structural contour line (Plate 4-9), that this shale interval thins in response to the upper sand portion of the effective Injection Interval becoming more massive and thicker to the north of the -6,500 feet structural contour line. This more massive and thickening tendency is observed in all wells north of this structural contour line. This may indicate that during deposition of these barrier sands, this area was structurally low. This is especially true for the northern area of the AOR (Plates 4-9). The net sand thickness for the WDW-165 Injection Interval ranges between 400 feet and 550+ feet within the AOR. The net thickness variations, as illustrated on the net thickness map (Plate 4-10), are related to the rates of subsidence, uplift, faulting, and attendant sea transgressions and regressions, at the time of deposition in the given areas of the AOR.